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An Electric and Magnetic Field Sensor for Simultaneous Electromagnetic Near-Field Measurements—Theory

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An Electric and Magnetic Field Sensor for Simultaneous Electromagnetic Near-Field Measurements—Theory

Motohisa Kanda

Electromagnetic Fields Division
National Engineering Laboratory
National Bureau of Standards
Boulder, Colorado 80303

U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, Secretary

NATIONAL BUREAU OF STANDARDS, Ernest Ambler, Director

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Motohisa Kanda

Electromagnetic Fields Division
National Bureau of Standards
Boulder, Colorado 80303

This paper describes the theory of a single sensor to perform simultaneous electric and magnetic near-field measurements. The theory indicates that it is possible to obtain the magnetic-loop and electric-dipole currents using a loop terminated with identical loads at diametrically opposite points. The theory also indicates that it is possible to obtain an ideal load impedance for achieving equal electric and magnetic field responses of the loop. Preliminary experiments have been performed using plane waves to verify these results.

Key words: electric field, electromagnetic interference, electromagnetic radiation, loop, magnetic field, near fields.

I. Introduction

At distances remote from the radiating source, the electromagnetic (EM) fields are comparatively easy to characterize, and the methods for doing so are quite well known. Of major importance, from the standpoint of biological effects and electromagnetic interference (EMI), is an accurate picture of the near field in regions close to electromagnetic radiation and reradiation sources. The regions close to a source are most likely to contain high intensity fields. Unfortunately, such locations are also characterized by complicated field structures, including reactive (stored) and real (propagated) energies, standing and traveling waves, and irregular phase surfaces.

Susceptibility of equipment to electromagnetic fields, as well as the degree of EMI and biological hazards, is generally presumed to be proportional to the magnitude of the EM field. The heating of a lossy dielectric material (such as human tissue) and the potential for damage are proportional to the time-average value of the total magnitude of the electric field strength squared. It is closely related to the electric field energy density, another scalar quantity which involves E and the complex permittivity of the medium.

Similarly, the heating of a partially conducting material is proportional to the time-averaged value of the total magnitude of the magnetic field strength squared. The familiar power density or Poynting vector is not directly relatable to the electric or magnetic field magnitude alone, except when the field structure is quite simple, as with a single plane wave.

Most conventional field intensity meters with relatively directive antennas cannot reliably measure complicated EM fields such as those with reactive near-field components, multipath reflections, unknown field polarization, multiple frequency components, complicated modulations, and large field gradients. For this reason, it has been a common practice to measure only the electric field strength or only the magnetic field strength. The sensor described in this paper represents an attempt to perform simultaneous, near-field electric and magnetic field measurements using a single antenna element. This kind of sensor is particularly needed for electromagnetic near-field measurements where the magnitude and phase angle of the wave impedance, which is a ratio of the electric field to the magnetic field, are not known. The field vectors are not necessarily orthogonal to each other and may be out of phase. Thus, this device is intended not only to measure the polarization ellipses of the electric and magnetic field vectors in the near-field region, but also to measure the time-dependent Poynting vector to describe the energy flow. This paper discusses the details of the theory and compares the theory with preliminary experimental results using plane waves.

II. Theory

II-1. Theory of Loop Antenna

Figure 1 shows the geometry and coordinate system for a loop antenna lying in the plane $z = 0$ and excited at $\phi = 0$ with a delta-function voltage source, V_0. Let us assume that a linearly polarized plane-wave, E^i, impinges onto the loop. Wu has shown [1] that the loop current $I(\phi)$ satisfies the integral equation

$$V_0 \delta(\phi) + b\, E_\phi^i(b,\phi) = \frac{j\zeta}{4\pi} \int_{-\pi}^{\pi} L(\phi-\phi')I(\phi')d\phi'. \tag{1}$$

Where $E_\phi^i(b,\phi)$ is the ϕ-component of the incident field at the point ϕ on the loop, b is the loop radius, and ζ is the free space impedance. The kernel in (1) may be represented in the Fourier series form as

$$L(\phi-\phi') = \sum_{-\infty}^{\infty} a_n \, e^{-jn(\phi-\phi')} \tag{2}$$

with

$$a_n = a_{-n} = \frac{kb}{2}\left(N_{n+1} + N_{n-1}\right) - \frac{n^2}{kb} N_n \tag{3}$$

$$N_n = \frac{b}{4\pi^2} \int_{-\pi}^{\pi} d\psi \int_{-\pi}^{\pi} \frac{e^{jn(\phi-\phi')} e^{-jkr}}{r} \, d\phi \tag{4}$$

$$r = \sqrt{4b^2 \sin^2(\phi-\phi')/2 + 4a^2 \sin^2(\alpha/2)} \, , \tag{5}$$

where k is the free space wave number. Assuming that $a \ll b$ and $ka < 1$, Wu has shown [1] that N_n can be represented in terms of integrals of Bessel and Lommel-Weber functions [2].

$$N_o = \frac{1}{\pi} \ln \frac{8b}{a} - \frac{1}{2}\left[\int_o^{2kb} \Omega_o(x)dx + j \int_o^{2kb} J_o(x)dx\right] \tag{6}$$

$$N_n = N_{-n} = \frac{1}{\pi}\left[K_o\left(\frac{na}{b}\right) I_o\left(\frac{na}{b}\right) + C_n\right]$$

$$- \frac{1}{2} \int_o^{2kb} \left[\Omega_{2n}(x) + jJ_{2n}(x)\right] dx \, , \quad n \geq 1 \tag{7}$$

where

$$C_n = \ln 4n + \gamma - 2 \sum_{m=o}^{n-1} \frac{1}{2m+1} \, , \tag{8}$$

$K_o(x)$ is the modified Bessel function of the second kind, $I_o(x)$ is the modified Bessel function of the first kind, $\Omega_n(x)$ is the Lommel-Weber function, $J_n(x)$ is the Bessel function, and $\gamma = 0.5772 \ . \ . \ .$ is Euler's constant.

The loop current $I(\phi)$ can be expanded in the Fourier series,

$$I(\phi) = \sum_{-\infty}^{\infty} I_n e^{-jn\phi} , \tag{9}$$

and the electric field $E_\phi^i(b,\phi)$ in the Fourier series

$$E_\phi^i(b,\phi) = E_o^i \sum_{-\infty}^{\infty} f_n e^{-jn\phi} . \tag{10}$$

According to Fourier's theorem

$$f_n = \frac{1}{2\pi E_o^i} \int_{-\pi}^{\pi} E_\phi^i(b,\phi) e^{in\phi} d\phi . \tag{11}$$

It becomes clear from figure 2 that the ϕ component of the incident field at an angle ϕ on the loop is

$$E_\phi^i(b,\phi) = E_o^i[\cos\psi \cos(\phi-\phi_o) - \sin\psi \sin(\phi-\phi_o) \cos\theta] e^{jkb \cos(\phi-\phi_o)\sin\theta} . \tag{12}$$

Using the integral representation of the Bessel function,

$$J_n(z) = \frac{j^{-n}}{2\pi} \int_0^{2\pi} e^{jz\cos\phi} e^{jn\phi} d\phi , \tag{13}$$

one gets

$$f_n = j^{n-1}\cos\psi\, e^{-jn\phi_o} J_n'(kb \sin\theta) + j^n \sin\psi \cos\theta\, e^{-jn\phi_o} \frac{nJ_n(kb \sin\theta)}{kb \sin\theta} . \tag{14}$$

Using the orthogonality property of the function $e^{-jn\phi}$, one obtains from (1), (2), (9), and (10) the Fourier coefficient of the current

$$I_n = -\frac{j}{\pi\zeta} \frac{V_o + 2\pi b E_o^i f_n}{a_n} . \tag{15}$$

II-2. Inductance and Capacitance of Loop Antenna

By setting $E_o^i = 0$ in (15), the admittance of the loop antenna is given by

$$Y = -\frac{j}{\pi\zeta}\sum_{-\infty}^{\infty}\frac{1}{a_n} = -\frac{j}{\pi\zeta}\left(\frac{1}{a_o} + 2\sum_{1}^{\infty}\frac{1}{a_n}\right) . \qquad (16)$$

Assuming that currents of higher order than n = 1 in (15) are negligible due to the small size of the loop, we can define the admittance for the magnetic-loop current (n = 0) as

$$Y_o = -\frac{j}{\pi\zeta a_o} \qquad (17)$$

and the admittance for the electric-dipole current (n = 1) as

$$Y_1 = -\frac{j2}{\pi\zeta a_1} . \qquad (18)$$

As will be shown later, the imaginary part (susceptance) of the loop admittance for the magnetic-loop current is generally negative and is, therefore, inductive. On the other hand, the susceptance for the electric-dipole current is generally positive and is, therefore, capacitive. Thus, from the slopes of the susceptance curves plotted against frequency, the quasi-static inductance and the quasi-static capacitance of the loop can be determined.

We impose the quasi-static limit (kb ≪ 1). To determine the admittance Y_o for this current, we require the relations

$$a_o = \frac{kb}{2}\left(N_1 + N_{-1}\right) = kb\ N_1 \qquad (19)$$

$$K_o\left(\frac{a}{b}\right) \cong -\left(\gamma + \ln\frac{a}{2b}\right) \qquad (20)$$

$$I_o\left(\frac{a}{b}\right) \cong 1 \qquad (21)$$

$$\Omega_2(x) \cong -\frac{2x}{3\pi} \tag{22}$$

$$J_2(x) \cong \frac{x^2}{8} . \tag{23}$$

To evaluate a_0, we obtain N_1 from (7) and neglect the higher powers of kb,

$$N_1 \cong \frac{1}{\pi}\left(\ell n\frac{8b}{a} - 2\right) + O\left(k^2b^2\right) . \tag{24}$$

From (17), we now obtain the quasi-static admittance for the magnetic-loop current,

$$Y_0 = \frac{1}{j\,\zeta kb\,\left(\ell n\frac{8b}{a} - 2\right)} = \frac{1}{j\omega L} \tag{25}$$

from which the inductance of the loop is

$$L = \mu b\left(\ell n\frac{8b}{a} - 2\right) , \tag{26}$$

where μ is the permeability of the medium.

Since $\ell n\, b/a > 1$ in general, the inductance of the loop is given approximately by the well-known formula,

$$L = \mu b\ \ell n\frac{b}{a} . \tag{27}$$

To obtain the quasi-static capacitance for the loop from (18), we require

$$a_1 = \frac{kb}{2}\left(N_2 + N_0\right) - \frac{1}{kb}N_1 \tag{28}$$

and, thus, also N_0, N_1, and N_2. Since

$$\Omega_0(x) \cong \frac{2}{\pi}x \tag{29}$$

$$J_0(x) \cong 1 \tag{30}$$

we obtain N_0 from (6), to the first order in kb,

$$N_0 \cong \frac{1}{\pi} \ln\frac{8b}{a} - jkb \ . \tag{31}$$

Also with

$$\Omega_4(x) \cong -\frac{2x}{15\pi} \tag{32}$$

$$J_4(x) \cong \frac{x^4}{2^4 4!} \cong 0 \tag{33}$$

so that, neglecting kb in higher orders, N_2 becomes

$$N_2 = \frac{1}{\pi}\left[-\ln\frac{a}{b} - \gamma + C_2\right] + \frac{1}{2}\int_0^{2kb} \frac{2x}{15\pi}\,dx \cong \frac{1}{\pi}\left[-\ln\frac{a}{b} - \gamma + C_2\right] \ . \tag{34}$$

where $C_2 = \ln 8 + \gamma - \frac{8}{3} \cong -0.010$.

Using the N_1 given in (24), the leading term of the admittance for the electric-dipole current is

$$Y_1 = -\frac{j2}{\pi\zeta a_1} \cong \frac{j2}{\pi\zeta}\frac{kb}{N_1} = \frac{j2}{\zeta}\frac{kb}{\left(\ln\frac{8b}{a} - 2\right)} = j\omega C \ . \tag{35}$$

Thus the capacitance of the loop is given by

$$C = \frac{2\varepsilon b}{\ln\frac{8b}{a} - 2} \ . \tag{36}$$

Since $\ln b/a \gg 1$ in general, the capacitance of the loop is approximately

$$C = \frac{2\varepsilon b}{\ln\frac{b}{a}} . \tag{37}$$

II-3. Electric and Magnetic Responses of Loop Antenna

Let us consider a small loop with two gaps at diametrically opposite points ($\phi = 0,\pi$) and loaded with equal impedances, Z_L, in an incident plane-wave field as shown in figure 1. Since the total current is the sum of the currents maintained by the electromagnetic forces at $\phi = 0, \pi$, and by the incident field E_ϕ^i,

$$I(\phi) = 2\pi b E_0^i u(\phi) - I(0)Z_L v(\phi) - I(\pi)Z_L w(\phi) \tag{38}$$

where

$$u(\phi) = -\frac{1}{\pi\zeta}\left(\frac{f_0}{a_0} + \frac{2f_1\cos\phi}{a_1}\right) \tag{39}$$

$$v(\phi) = -\frac{j}{\pi\zeta}\left(\frac{1}{a_0} + \frac{2\cos\phi}{a_1}\right) \tag{40}$$

$$w(\phi) = -\frac{j}{\pi\zeta}\left(\frac{1}{a_0} - \frac{2\cos\phi}{a_1}\right) . \tag{41}$$

Here it is assumed that currents of higher order than n = 1 in (15) are negligible due to the small size of the loop. The current I(0) and I(π) can be determined from the simultaneous equations obtained from (38) with ϕ = 0 and π.

$$I(0) = 2\pi b E_0^i \left(\frac{f_0 Y_0}{1 + 2Y_0 Z_L} + \frac{f_1 Y_1}{1 + 2Y_1 Z_L}\right) \tag{42}$$

$$I(\pi) = 2\pi b E_o^i \left(\frac{f_o Y_o}{1 + 2Y_o Z_L} - \frac{f_1 Y_1}{1 + 2Y_1 Z_L}\right) , \tag{43}$$

where $Y_o = G_o + jB_o$ is the loop admittance for the magnetic-loop response and $Y_1 = G_1 + jB_1$ is the loop admittance for the electric-dipole response.

By taking the sum and difference of these currents, one can obtain

$$I_\Sigma = \frac{1}{2}\left(I(0) + I(\pi)\right) = 2\pi b E_o^i \frac{f_o Y_o}{1 + 2Y_o Z_L} \tag{44}$$

$$I_\Delta = \frac{1}{2}\left(I(0) - I(\pi)\right) = 2\pi b E_o^i \frac{f_1 Y_1}{1 + 2Y_1 Z_L} . \tag{45}$$

It can be seen from (44) and (45) that the sum current is used to measure the magnetic field, whereas the difference current is used to measure the electric field.

One can verify the results in (44) and (45) by considering the currents in the electric-dipole and magnetic field responses of the loop. Across one load, the magnetic-loop response adds to the electric-dipole response, whereas, across the other load the magnetic-loop response subtracts from the electric-dipole response. Thus, by taking the sum and difference of currents across loads at diametrically opposite points, the magnetic-loop response and electric-dipole response can be separated. That is, the sum current gives a measure of the magnetic field, whereas the difference current gives a measure of the electric field.

For a loop orientation with maximum electric and magnetic field responses, i.e., $\psi = 0$, $\theta = \pi/2$, and $\phi_o = 0$, one gets from (14)

$$f_o \cong j \frac{kb}{2} \tag{46}$$

and

$$f_1 \cong \frac{1}{2} \tag{47}$$

since for small arguments

$$J_0'(z) = -J_1(z) \cong -\frac{1}{2} z \tag{48}$$

and

$$J_1'(z) = J_0(z) - \frac{1}{z} J_1(z) \cong \frac{1}{2} . \tag{49}$$

In general, $2Y_0Z_L > 1$ for the magnetic-field loop current. Therefore, one can make the following approximation,

$$I_\Sigma \cong j\frac{E_0^i}{2Z_L} \pi b^2 k , \tag{50}$$

which indicates that the magnetic-loop current is approximately proportional to the product of frequency and the area of the loop, and inversely proportional to the load impedance. Similarly for the electric-field dipole current, assuming that
$2Y_1Z_L \ll 1$,

$$I_\Delta \cong \pi b E_0^i \, Y_1 , \tag{51}$$

which is approximately proportional to the product of the circumference of the loop and frequency since Y_1 has a capacitive susceptance (positive) and increases with frequency.

III. Theoretical and Experimental Results

The real (conductance) and imaginary (susceptance) parts of the loop admittance with the loop radius, b, of 0.16 m, and the wire radius, a, of 0.02 m, calculated using (16), are shown in figures 3 and 4, respectively. Figure 4 indicates that the susceptance, B_0, for a magnetic-loop response is inductive (negative) and inversely proportional to frequency, whereas the susceptance, B_1, for an electric-dipole response is capacitive (positive) and proportional to frequency. The inductance L and the capacitance C of the loop in the above example can be calculated using (26) and (36) to obtain

$$L = \mu b(\ell n\frac{8b}{a} - 2) \cong 0.44 \ \mu H \tag{52}$$

and

$$C = \frac{2\varepsilon b}{\ln\frac{8b}{a} - 2} \cong 1.31 \text{ pF} . \tag{53}$$

From figure 4, the first loop resonance is near 124 MHz since the total susceptance (the sum of admittances due to magnetic-loop response, electric-dipole response, and higher order modes) approaches zero at that frequency. Since the loop displays a very high resistance at the first resonance as indicated in figure 5, this resonance is not commonly used in all practical purposes. Figure 5 indicates that the second loop resonance is near 210 MHz. This agrees very well with the resonance frequency estimated from the inductance and capacitance given in (52) and (53).

The real (resistance) and imaginary (reactance) parts of the loop impedance are shown in figures 5 and 6. Figure 5 indicates that the loop resistance of an electric-dipole response is larger than that of a magnetic-loop response up to 260 MHz, whereas the loop resistance of a magnetic-loop response becomes larger than that of an electric-dipole response above 260 MHz.

The sum and difference currents in the loop with Z_L = 200 Ω, calculated using (44) and (45), are shown in figure 7. The real part of the currents increases with frequency up to about 200 MHz as indicated in (50) and (51). With a load impedance of 200 Ω, the magnetic-loop current is larger than the electric-dipole current up to 100 MHz, whereas the electric-dipole current becomes larger than the magnetic-loop current above 100 MHz.

To verify the above results experimentally, as shown in figure 7, we have constructed a loop with a radius of 0.16 m and wire radius of 0.02 m, as shown in figure 8. The loop is loaded at two diametrically opposite points with resistances of 200 Ω by using 4:1 baluns and 50 Ω resistive loads. To separate the mode currents, a 0°/180° hybrid is used to obtain the sum and difference of the currents. Zero-bias Schottky diodes are used as detectors, employing high-resistance plastic transmission lines between the antenna and a high input impedance dc voltmeter. The loop sensor is placed in the known

electromagnetic field inside a transverse electromagnetic (TEM) cell. After taking into account diode detection efficiencies [3], the experimentally measured loop currents for an incident electric field of 1 V/m are shown in figure 7. Although there is some discrepancy between the theory and preliminary experimental results, which may be associated with the balun impedances, the results indicate a general validity of the theory. For further reference, the sum and difference currents in the loop with Z_L = 50, 100, and 1000 Ω are shown respectively in figures 9, 10, and 11. The real parts of the magnetic-loop and electric-dipole components of the loop current, with various load impedances as a function of frequency, are summarized in figure 12.

Figures 13, 14, 15, and 16 show, respectively, the real parts of the magnetic-loop and electric-dipole currents as a function of its load impedance at 1, 10, 30, and 100 MHz. It indicates that there is a critical load impedance, for example 260 Ω at 10 MHz, for which the magnetic field response of the loop is equal to the electric field response of the loop. Below this critical load impedance, the magnetic-loop current is greater than the electric-dipole current. Above this critical load impedance, the electric-dipole current is larger than the magnetic-loop current. It is also found from figure 17 that this critical load impedance has only a slight frequency dependence, ranging from 200 to 260 Ω for the frequency range of 1 to 100 MHz.

IV. Conclusions

This paper describes a concept by which a single sensor is capable of performing simultaneous electric and magnetic field measurements. The sensor considered is a loop antenna terminated with identical loads at diametrically opposite points. Theory indicates that by taking the sum and difference of the loop currents at each load, the electric-field and magnetic-field responses can be separated. In our preliminary experiments using plane waves, a quadrature 3 dB 90° hybrid was used to obtain the sum and difference currents in the loop. Further, the theory also indicates that it is possible to adjust electric and magnetic field responses of the loop, by changing load impedances, to obtain equal electric and magnetic loop responses.

It is envisioned that this kind of sensor may be used to measure not only the polarization ellipses of the electric and magnetic vectors in the near-field region, but also to measure the time-dependent Poynting vector. From the Poynting vector it should be possible to describe the energy flow. Further work on this concept is being pursued.

V. References

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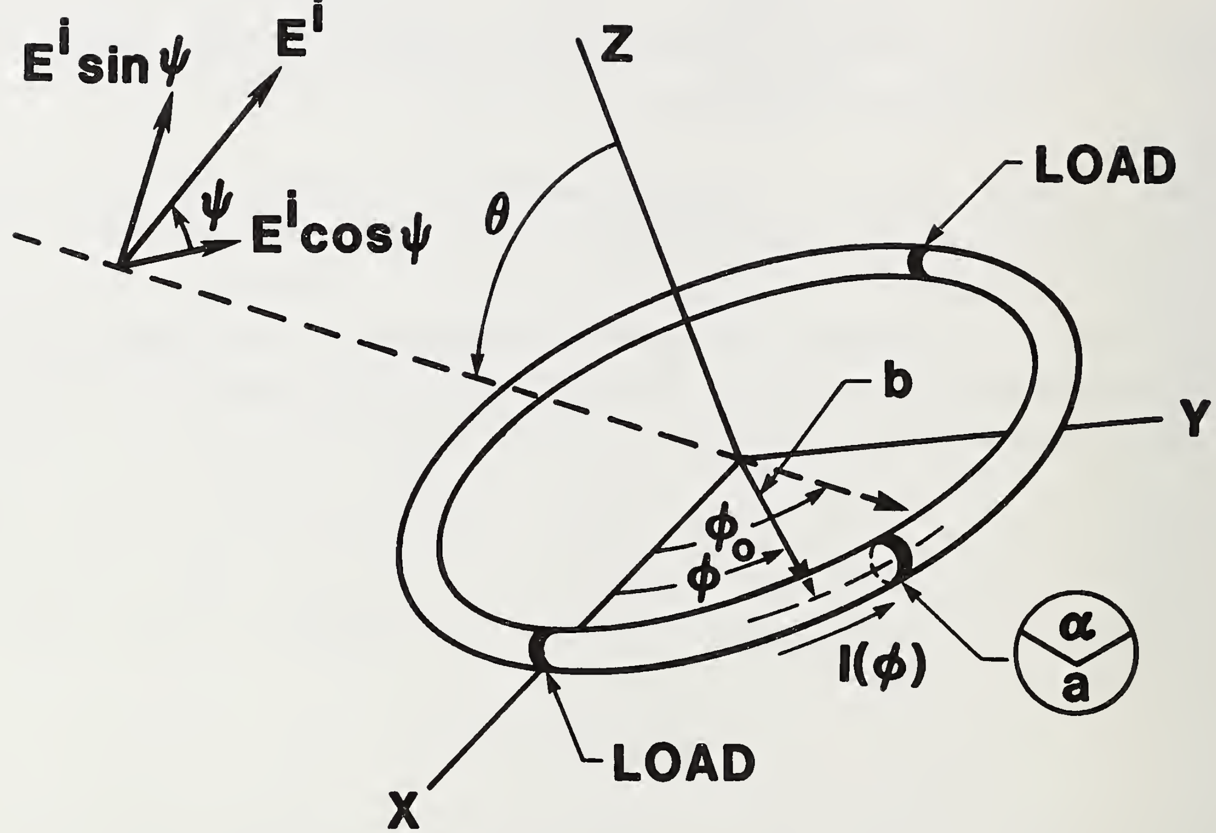

Figure 1. Loop configuration for simultaneous electric and magnetic field sensor.

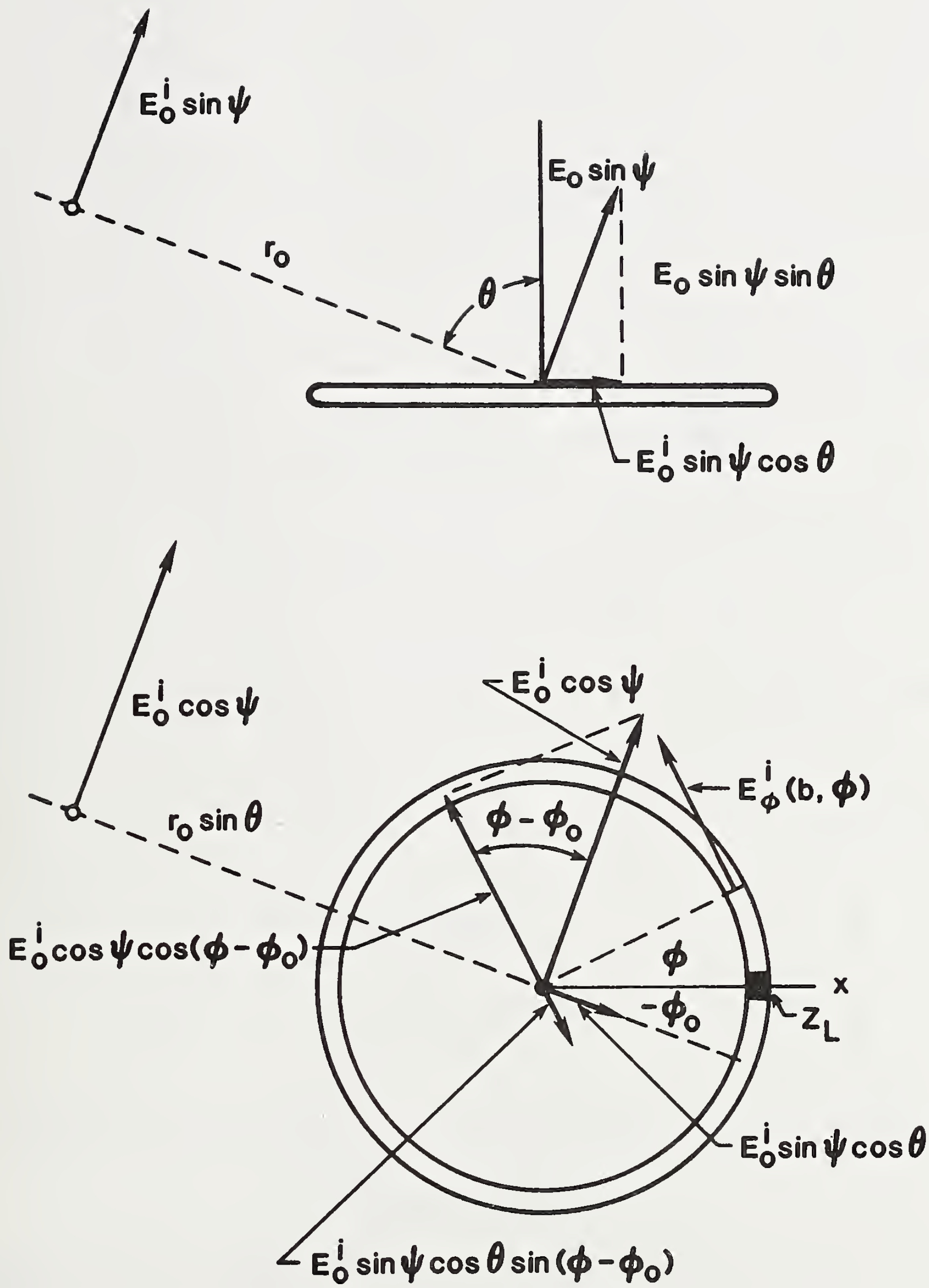

Figure 2. Receiving Loop in an incident plane-wave field.

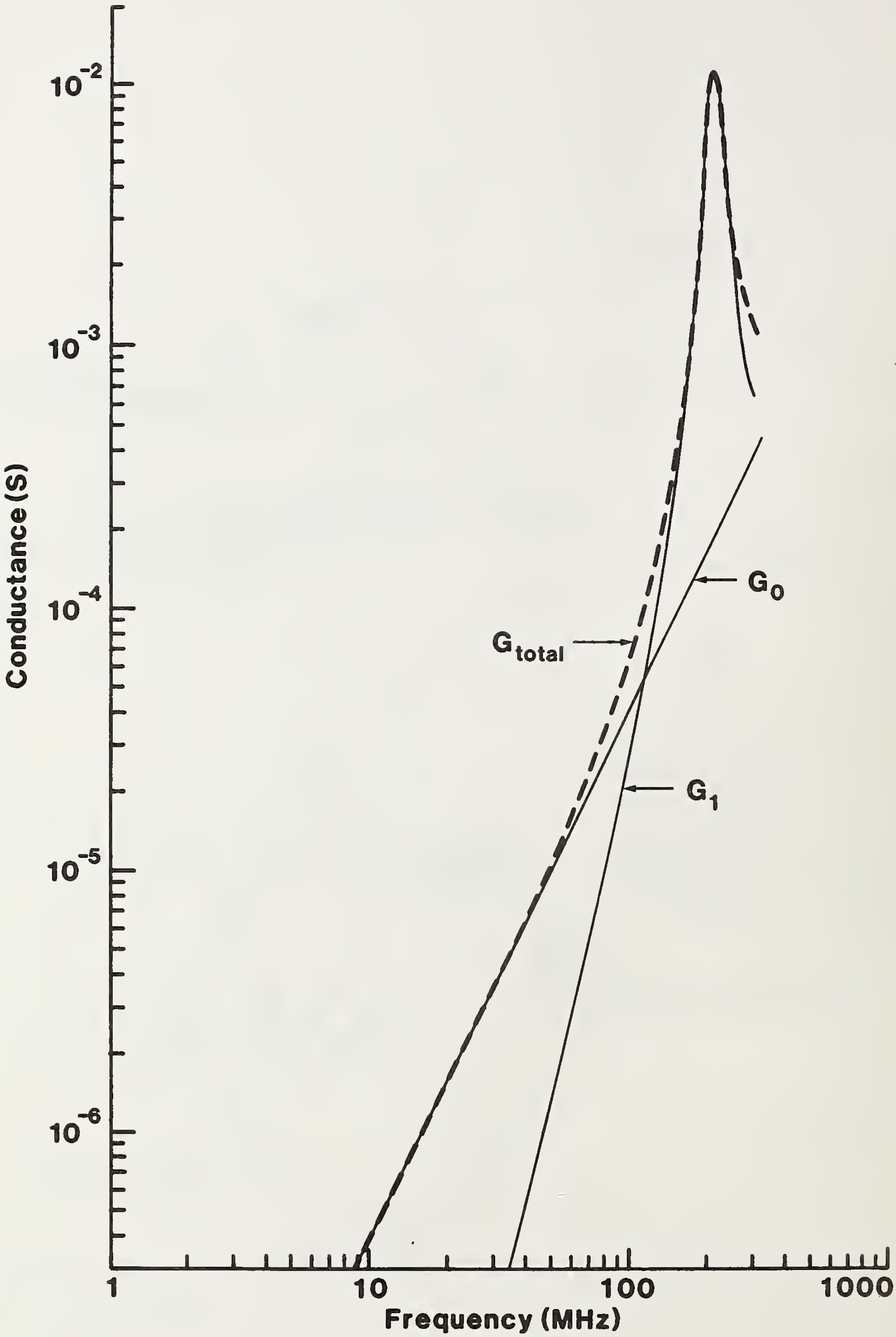

Figure 3. Conductance of loop antenna (a = 0.02 m, b = 0.16 m).

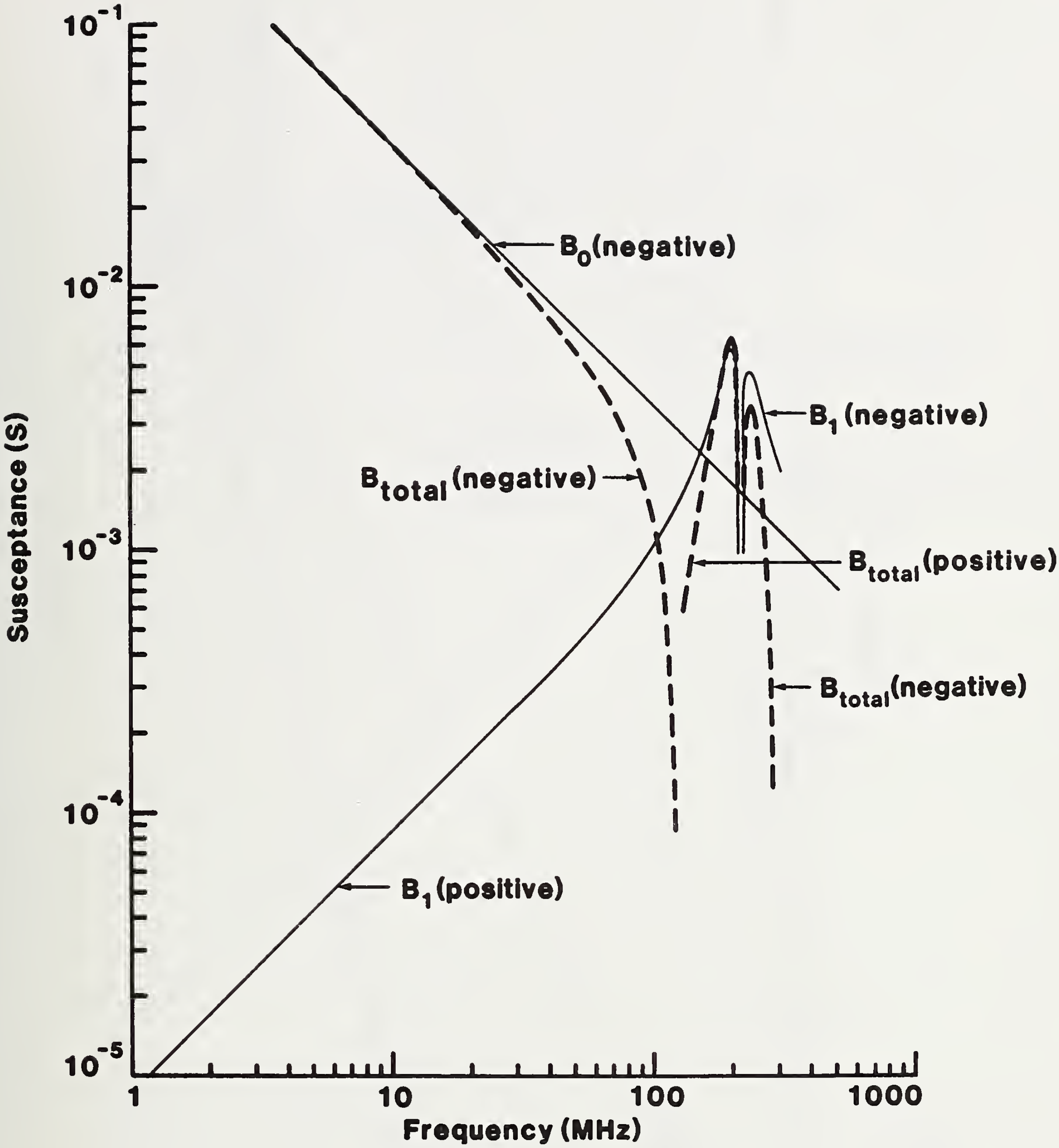

Figure 4. Susceptance of loop antenna (a = 0.02 m, b = 0.16 m).

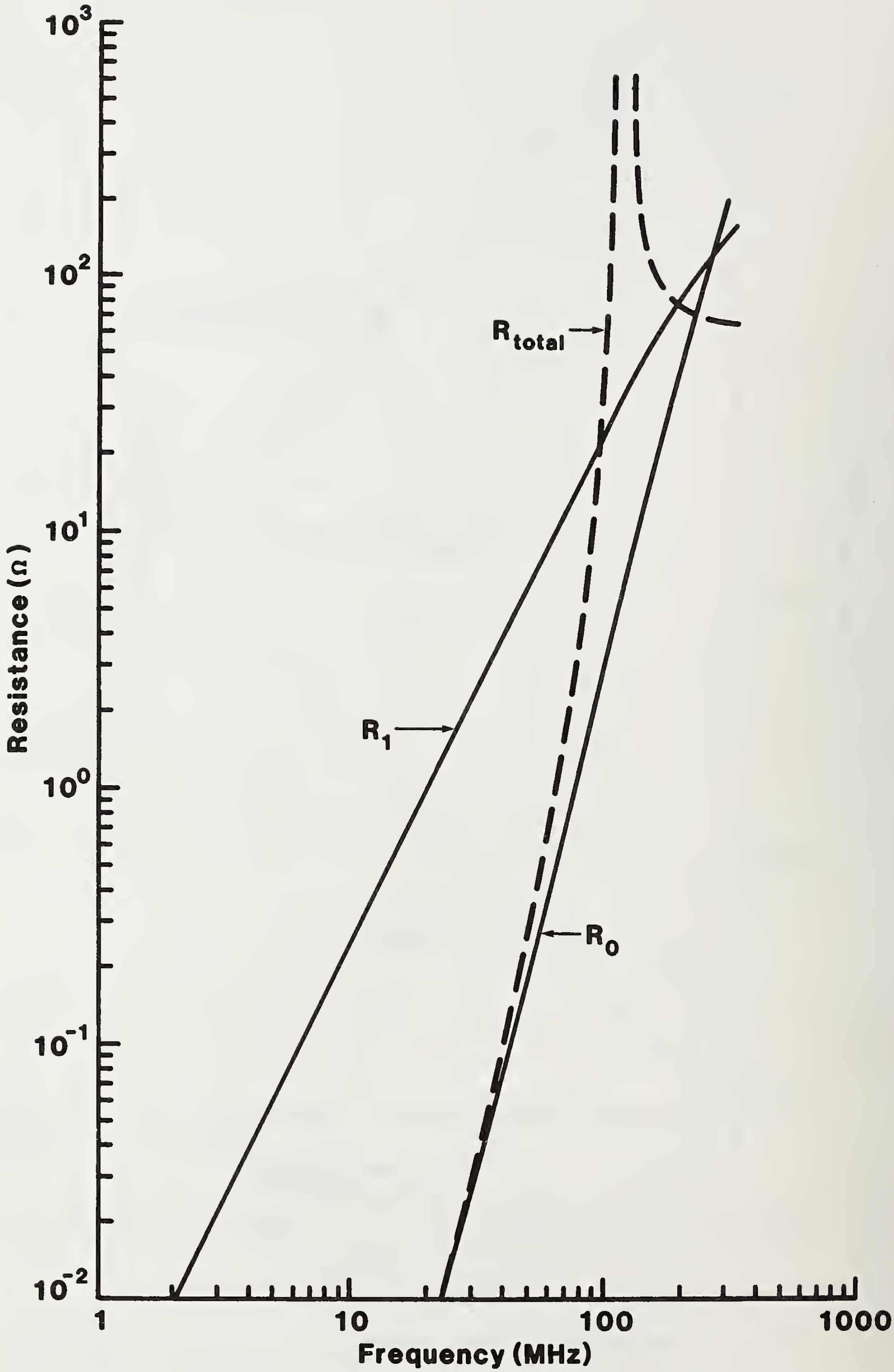

Figure 5. Resistance of loop antenna (a = 0.02 m, b = 0.16 m).

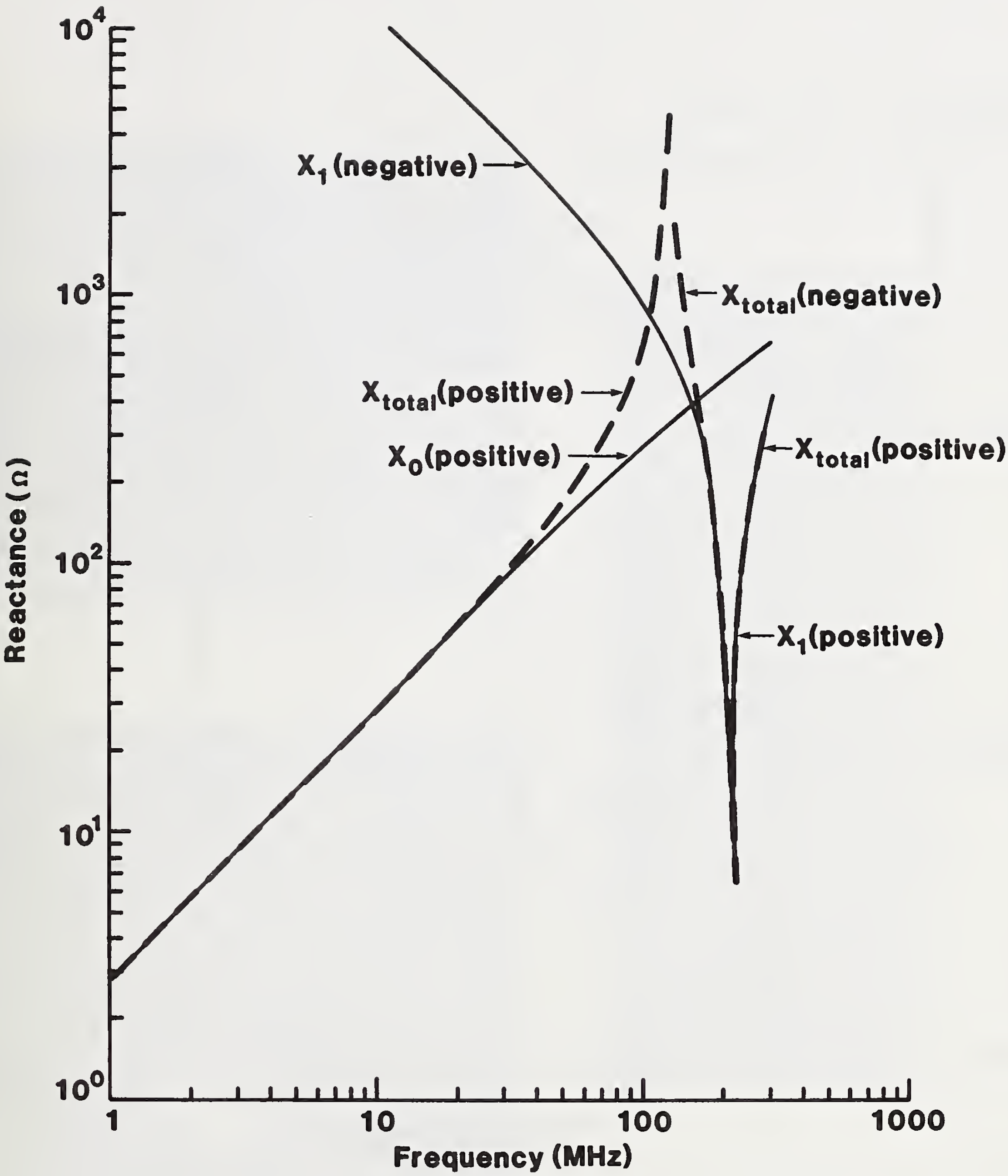

Figure 6. Reactance of loop antenna (a = 0.02 m, b = 0.16 m).

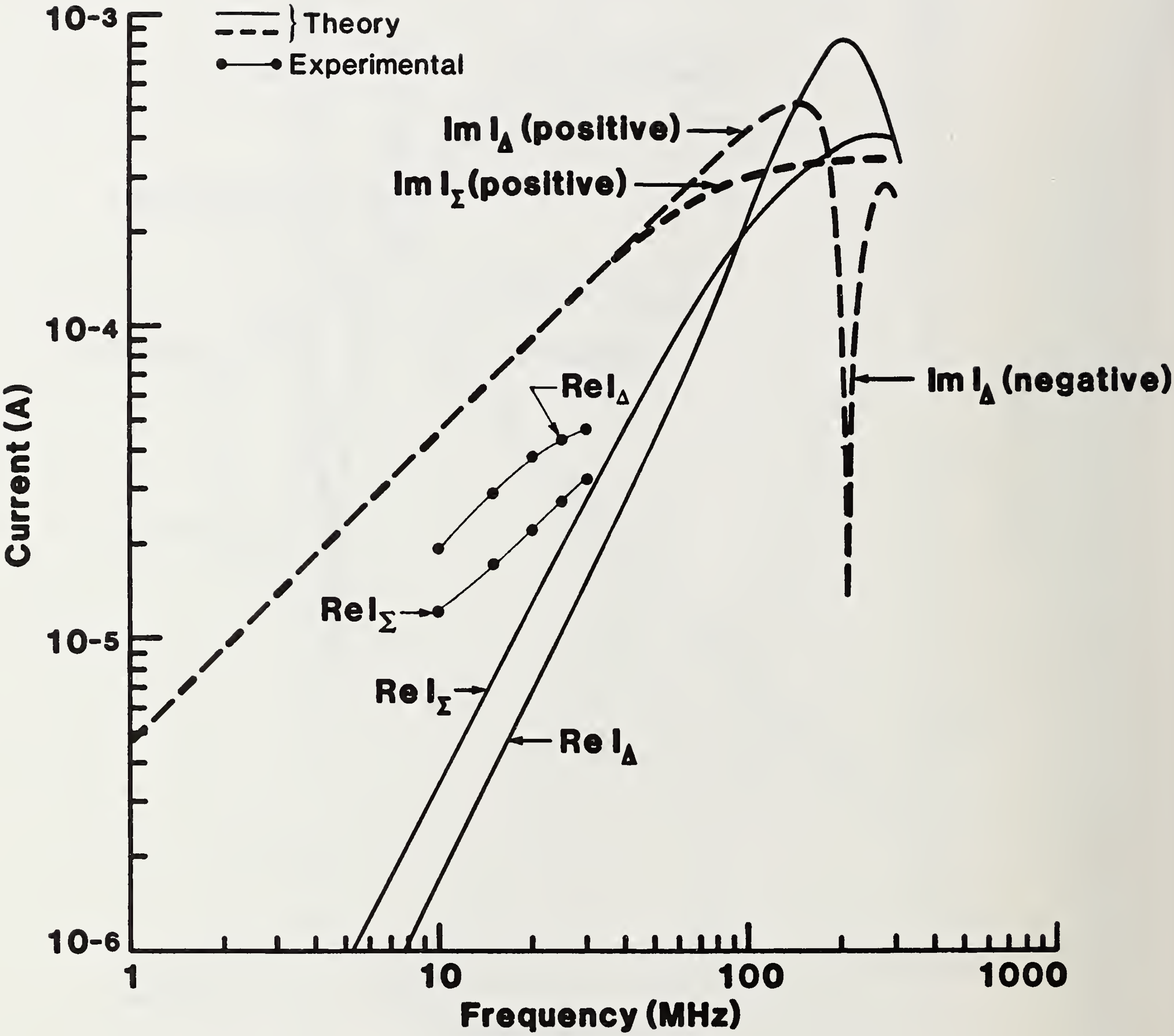

Figure 7. Magnetic-loop (I_Σ) and electric-dipole (I_Δ) currents of loop antenna (Z_L = 200 Ω).

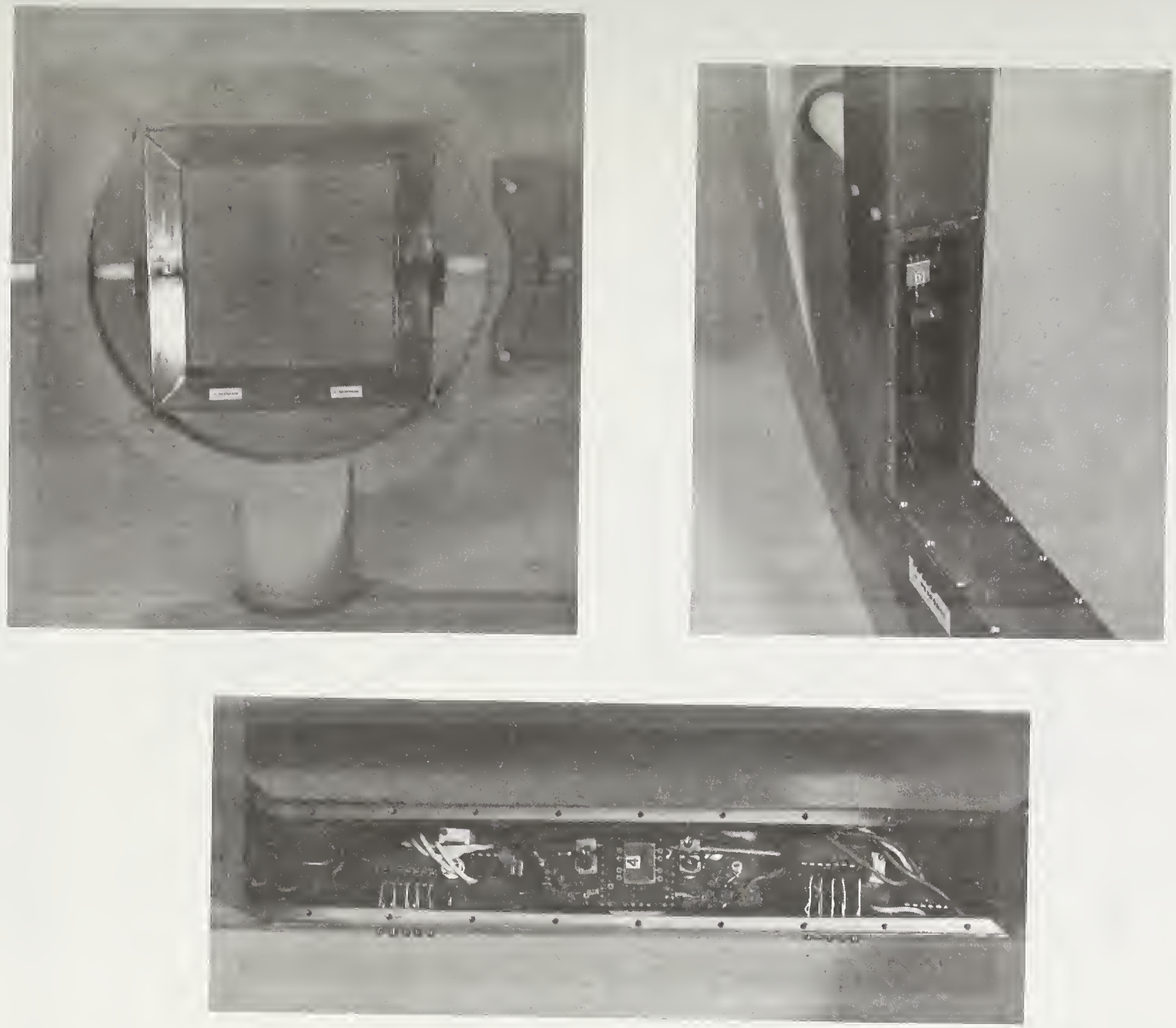

Figure 8. An electric and magnetic field sensor for simultaneous electromagnetic near-field measurements.

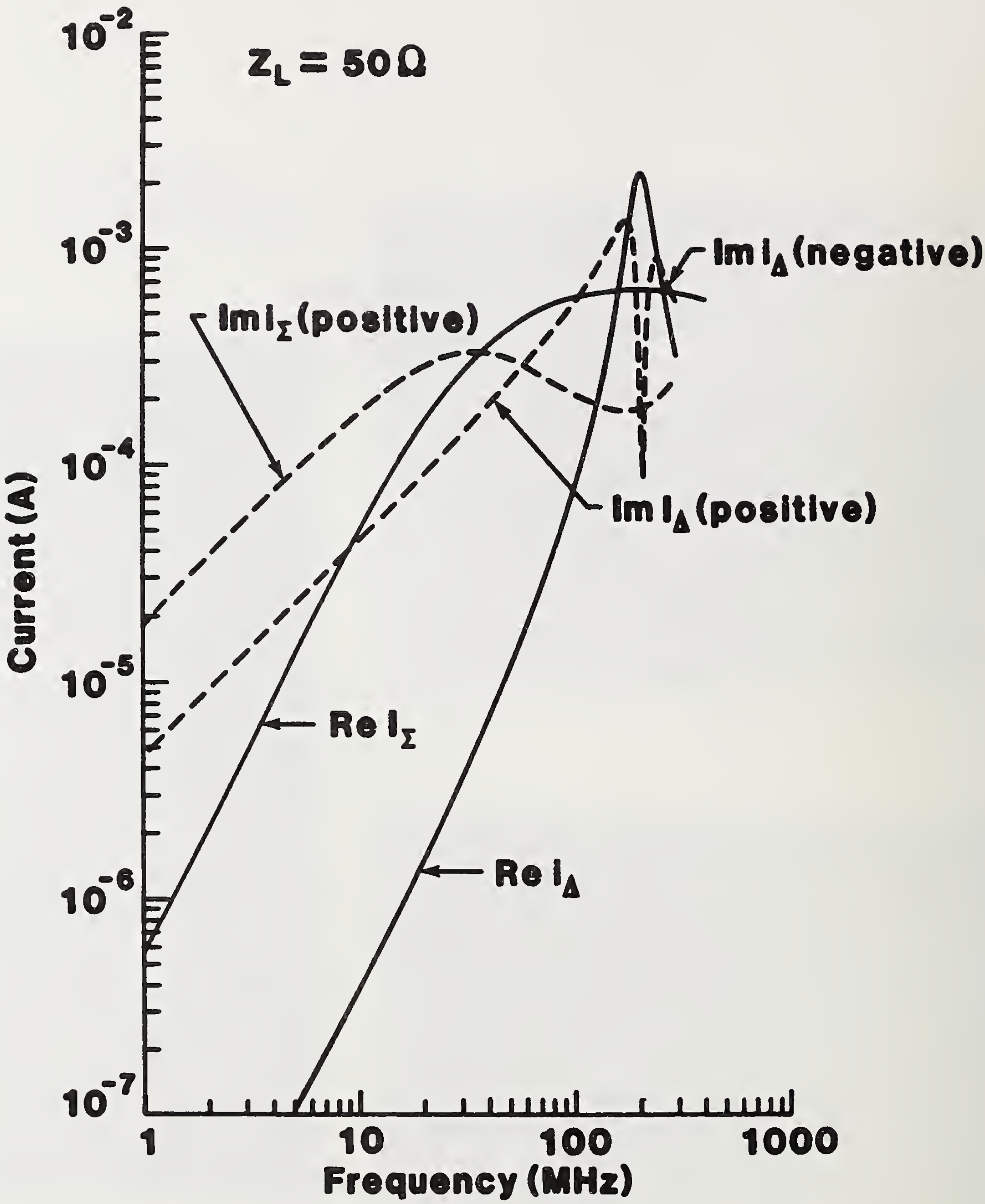

Figure 9. Magnetic-loop (I_Σ) and electric-dipole (I_Δ) currents of loop antenna (Z_L = 50 Ω).

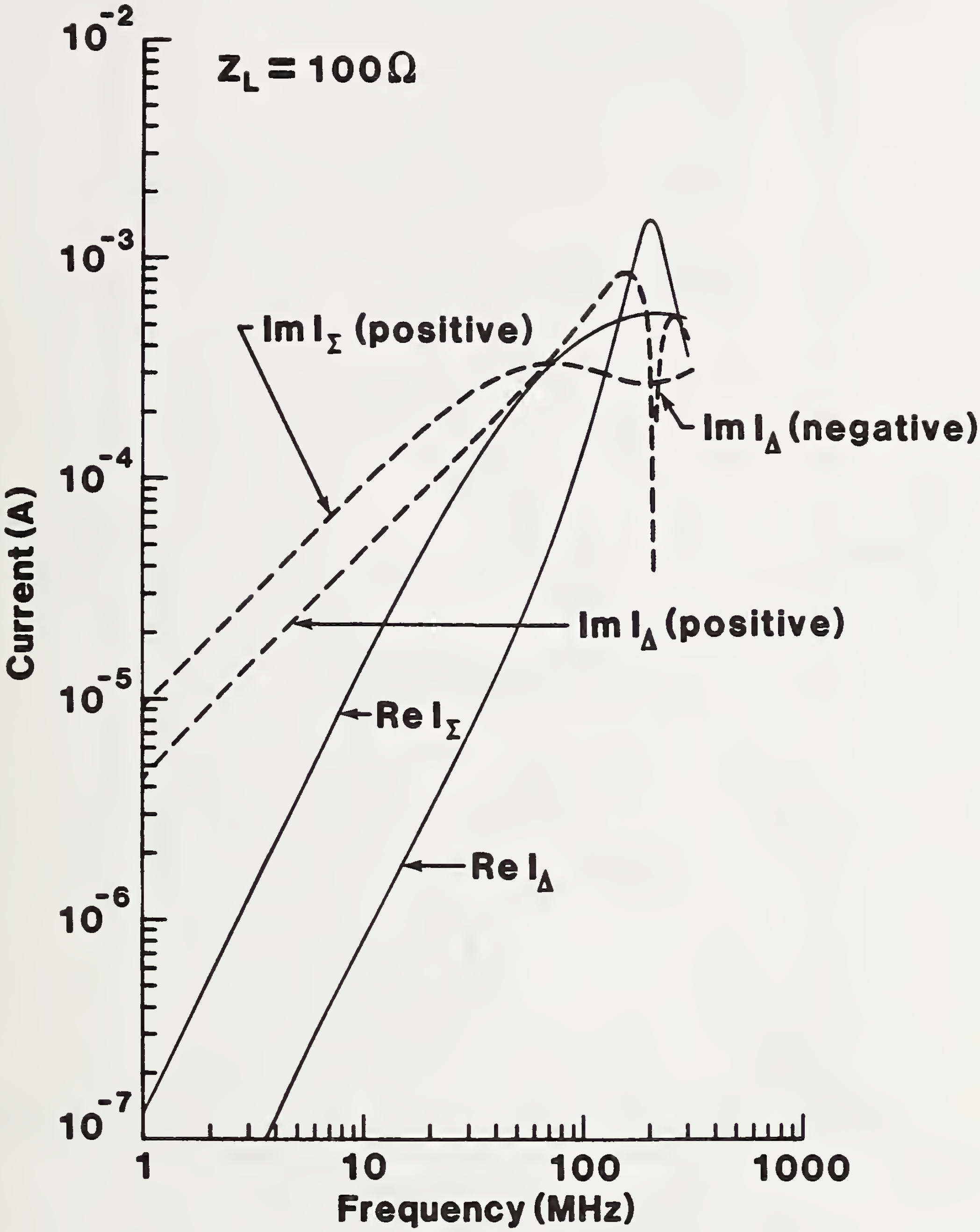

Figure 10. Magnetic-loop (I_Σ) and electric-dipole (I_Δ) currents of loop antenna (Z_L = 100 Ω).

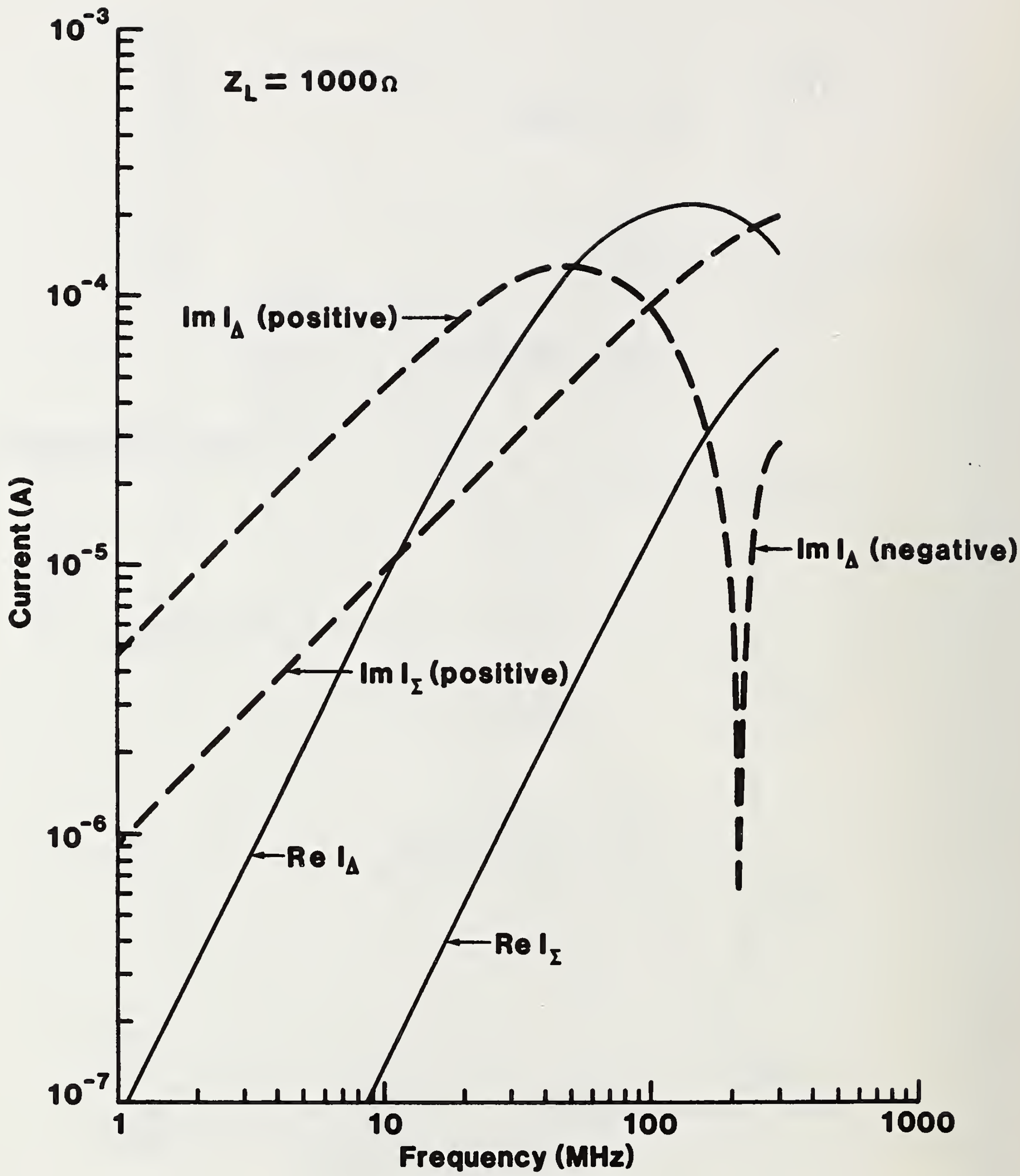

Figure 11. Magnetic-loop (I_Σ) and electric-dipole (I_Δ) currents of loop antenna (Z_L = 1000 Ω).

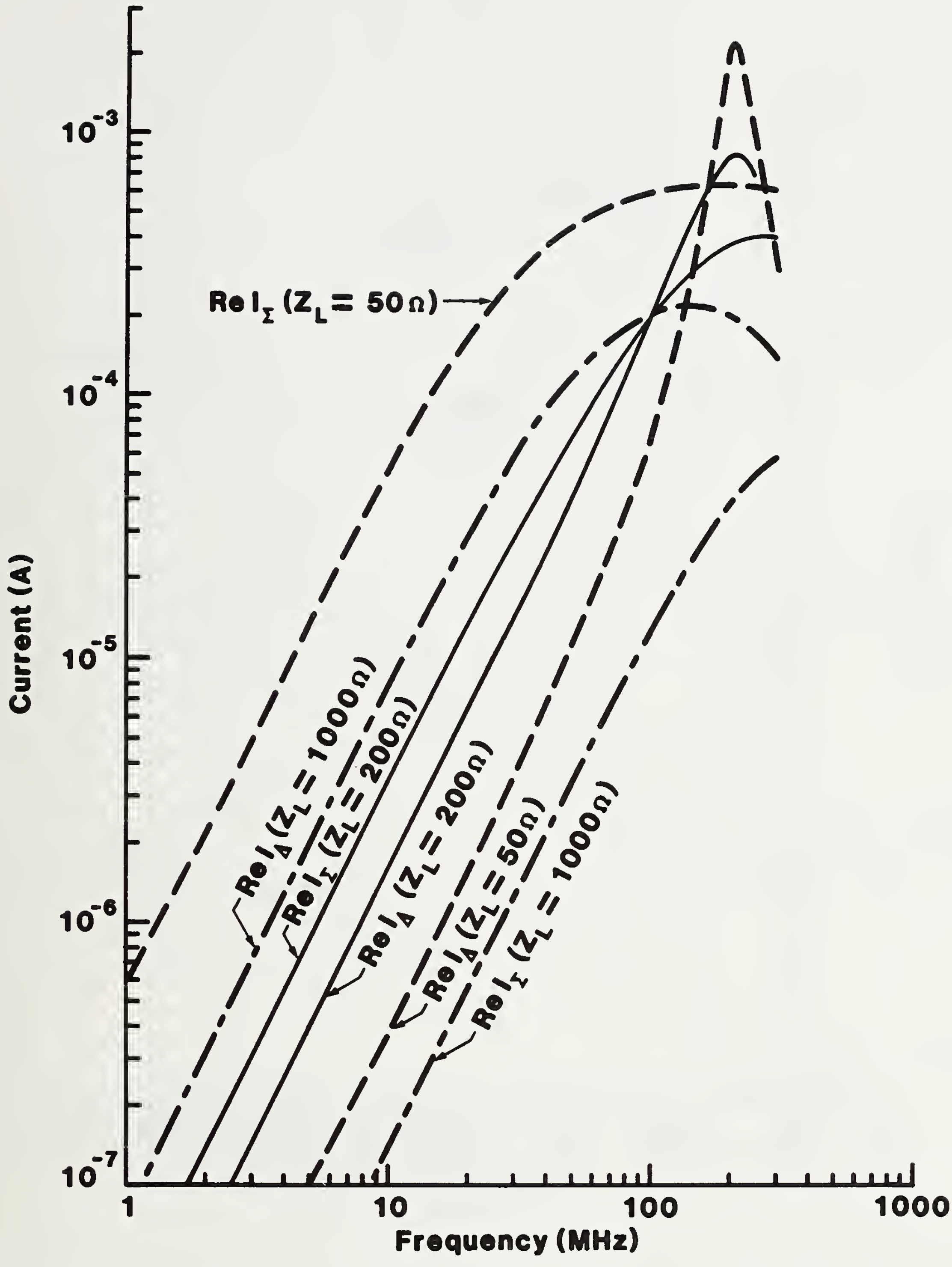

Figure 12. Real parts of magnetic-loop (I_Σ) and electric-dipole (I_Δ) currents of loop antenna with various load impedances.

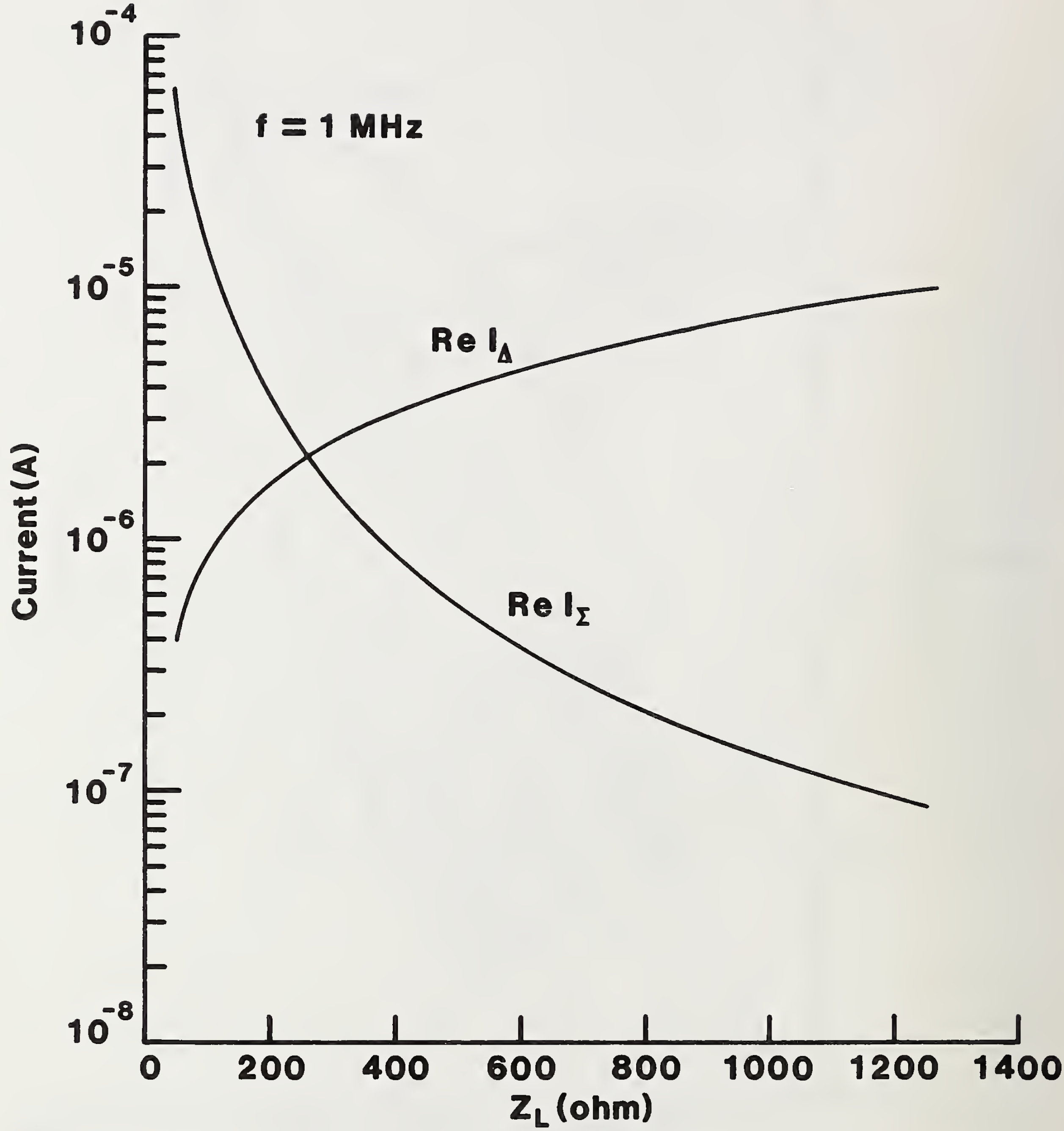

Figure 13. Real parts of magnetic-loop (I_Σ) and electric-dipole (I_Δ) currents of loop antenna as a function of load impedance at 1 MHz.

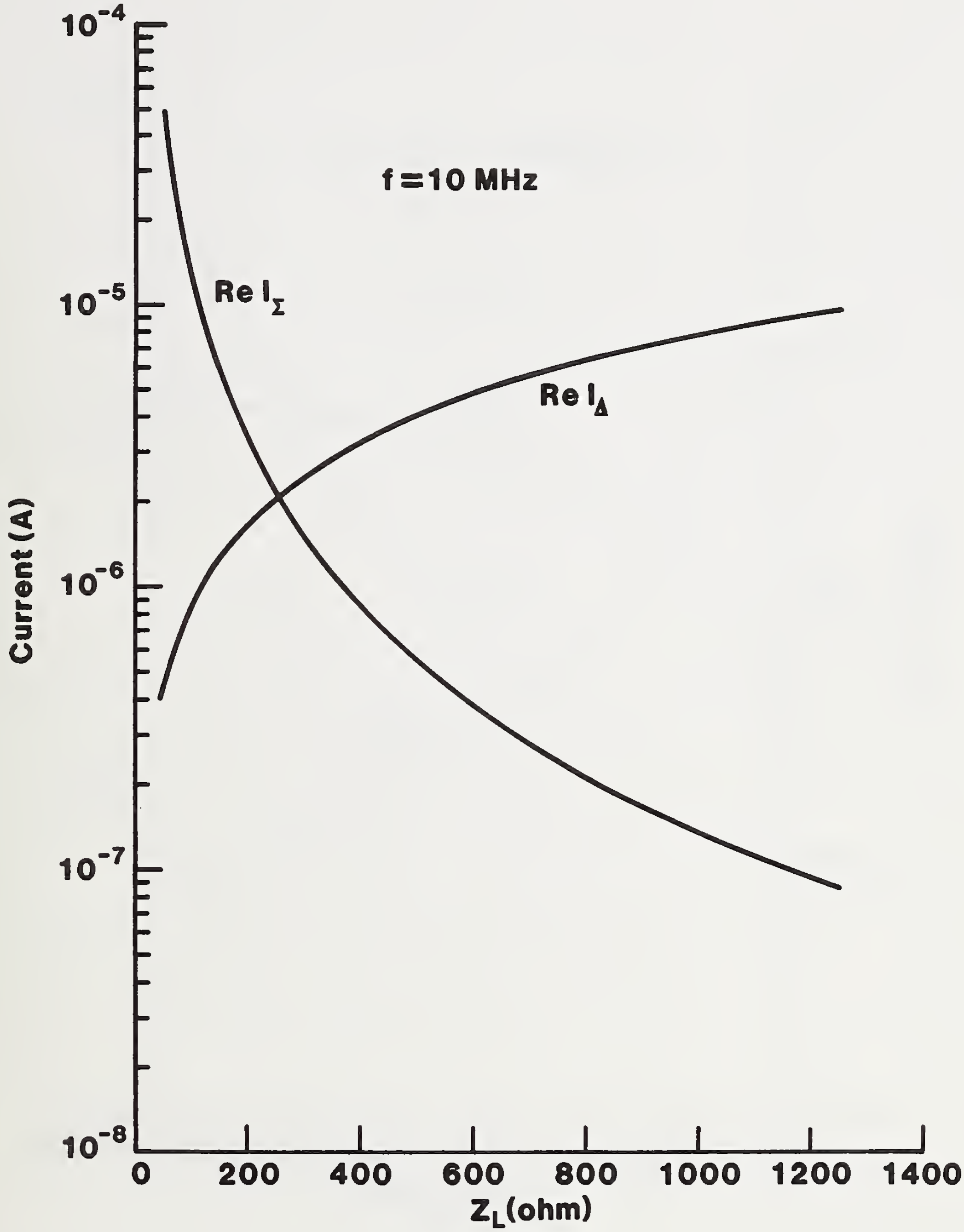

Figure 14. Real parts of magnetic-loop (I_Σ) and electric-dipole (I_Δ) currents of loop antenna as a function of load impedance at 10 MHz.

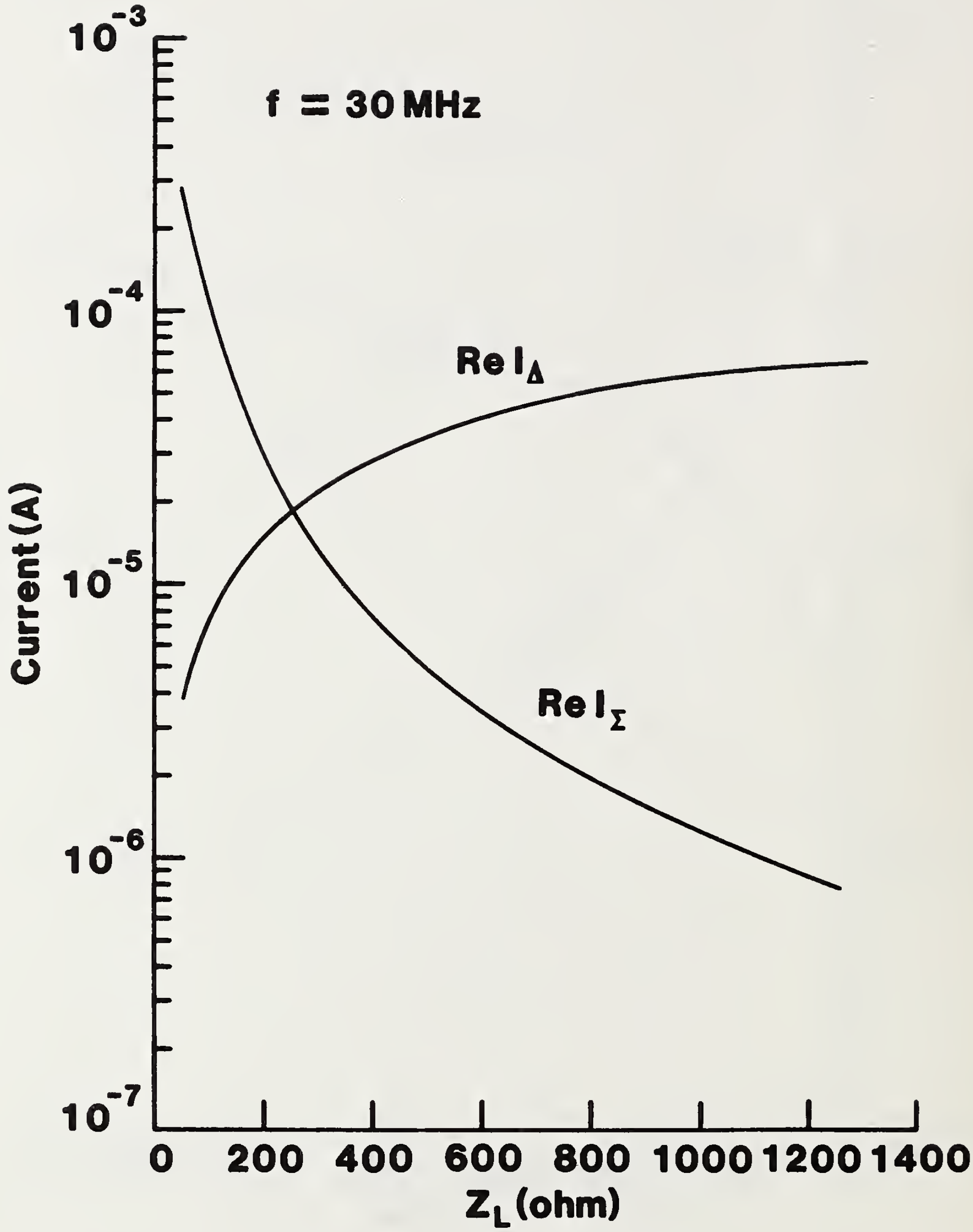

Figure 15. Real parts of magnetic-loop (I_Σ) and electric-dipole (I_Δ) currents of loop antenna as a function of load impedance at 30 MHz.

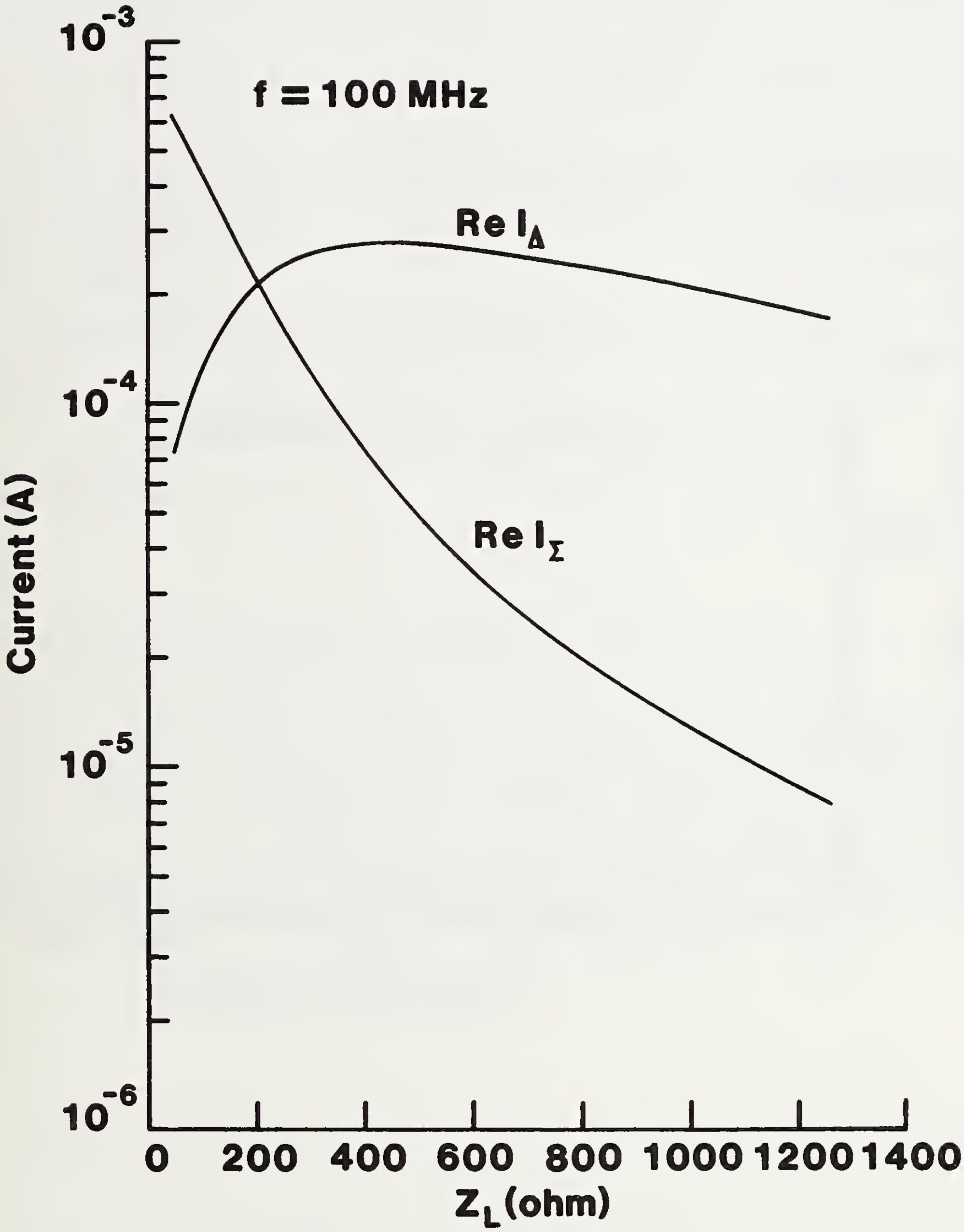

Figure 16. Real parts of magnetic-loop (I_{Σ}) and electric-dipole (I_{Δ}) currents of loop antenna as a function of load impedance at 100 MHz.

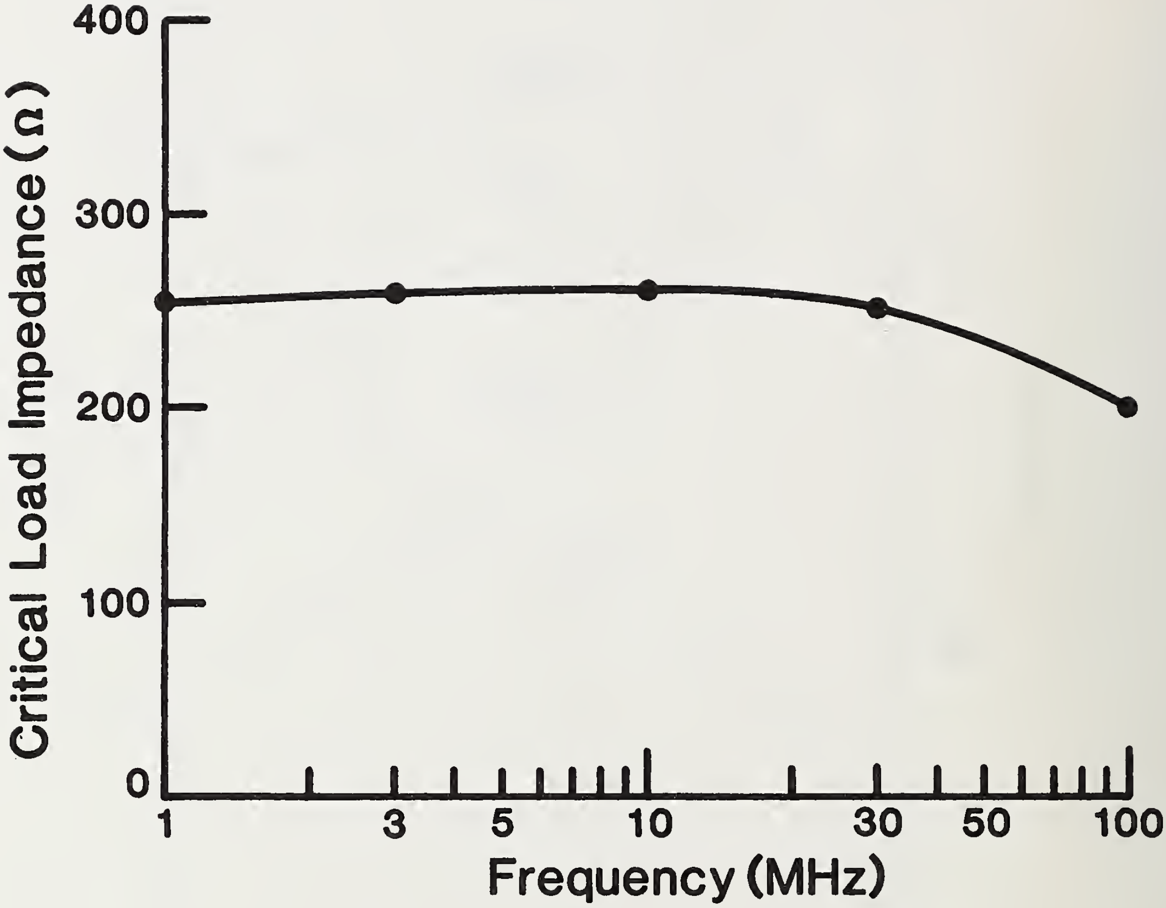

Figure 17. Critical load impedance of loop antenna as a function of frequency.

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11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*.

This paper describes the theory of a single sensor to perform simultaneous electric and magnetic near-field measurements. The theory indicates that it is possible to obtain the magnetic-loop and electric-dipole currents using a loop terminated with identical loads at diametrically opposite points. The theory also indicates that it is possible to obtain an ideal load impedance for achieving equal electric and magnetic field responses of the loop. Preliminary experiments have been performed using plane waves to verify these results.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

electric field; electromagnetic interference; electromagnetic radiation; loop; magnetic field; near fields.

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